LIMNOLOGICAL AND FISHERIES INVESTIGATIONS AT

VIRGINIA LAKE, SOUTHEAST ALASKA,

2000

by

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and
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ABSTRACT

The Virginia Lake nutrient enrichment program was continued in 2000. Fertilizer was applied at 60% of the critical phosphorus load, using both 32-0-0 liquid fertilizer that was applied weekly from mid-May to early September, and an 8-24-8 solid, controlled release fertilizer (CRF) that was placed into the lake monthly from May to September. Limnological sampling showed that phosphorus, chlorophyll a concentrations, and zooplankton density and biomass were at normal (low) levels throughout the 2000 growing season, and that phosphorus in the CRF likely did not disperse into the limnetic area of the lake. The fall rearing sockeye salmon fry population was estimated at 169,000 fish on 26 September 2000. The ZB-EZD model predicted the lake could support 132,000-219,000 fall fry. The 2000 rearing fry were not planted but were F_1 progeny of the adults that returned in 1998 and 1999 from the initial colonization program (1989 to 1996). Based on 12% marine survival, the predicted total adult return for 2001 is estimated at 14,175 (36% enhanced from the last fry plants in 1996) sockeye salmon.

KEY WORDS: sockeye salmon, *Oncorhynchus nerka*, Virginia Lake, Mill Creek, Porterfield Creek, Southeast Alaska, limnology, zooplankton, lake fertilization, nutrient enrichment, controlled release fertilizer, survival, rearing, hydroacoustics, mid-water trawl, fishpass

INTRODUCTION

Over the past 12 years a great deal of fisheries work has been conducted at Virginia Lake. Historically, Virginia Lake had a flow limiting natural barrier located just above tidewater that was size specific to the passage of fish, and allowed only a very small population of sockeye salmon *Oncorhynchus nerka* to utilize the lake (Zadina and Haddix 1993). In a cooperative effort, the U. S. Forest Service installed a fishpass in 1988, and the Alaska Department of Fish and Game and Southern Southeast Regional Aquaculture Association stocked the lake with sockeye salmon fry from 1989 to 1996 (Edmundson et al. 1991; Zadina and Haddix 1993; Zadina 1997). A nutrient enrichment program was initiated at Virginia Lake and fertilizer was applied at 90% of the critical phosphorus load (after Vollenweider 1976) every year that sockeye salmon fry were planted in the lake, from 1991 to 1996. After a hiatus in 1997, the nutrient enrichment program was reimplemented in 1998, with the critical phosphorus loading rate reduced to 50% (Zadina and Weller 1999). The intent was to increase trophic levels in Virginia Lake, primarily to the benefit of the resident cutthroat trout *Oncorhynchus clarki* population. Increasing the forage base for rearing sockeye salmon fry was a secondary goal of the lake fertilization program.

In 1999, Virginia Lake was fertilized at 50% of the critical phosphorus load, only this time all of the phosphorus added to the lake was contained in solid controlled release fertilizer (CRF) that was primarily distributed in the littoral zone of the upper half of the lake (Zadina and Heinl 2000). The results were mixed, however, and problems with the fertilizer application made it difficult to determine if solid fertilizer could be successfully used to increase the nutrient levels in the lake. In 2000, the lake was again fertilized with a combination of liquid and solid CRF; this time at 60% of the critical phosphorus load, with 25% of the solid fertilizer distributed in upper Porterfield Creek, approximately 6.4 km above the confluence with Virginia Lake.

Here we report the results of continued limnological studies at Virginia Lake during the 2000 field season. These studies included: (1) an assessment of the primary and secondary production in the lake; (2) an assessment of the lake fertilization application program; (3) an estimate of the rearing sockeye salmon fry population through hydroacoustic sampling; and (4) a forecast of the total adult return for 2001. The escapement, age structure, and coded wire tag recoveries of adult sockeye salmon returning to Virginia Lake were evaluated by U. S. Forest Service personnel and are not included in this report.

Study Site

Virginia Lake (56?20’ N. lat., 132?10’ W. long.) is located 16 km east of Wrangell on mainland Southeast Alaska at an elevation of 32 m (Figure 1). The lake is organically stained with a surface area of 256.7 ha, mean depth of 27.5 m, maximum depth of 54 m, and volume of $70.7 \cdot 10^6$ m^3 (Figure 2). The lake empties into Eastern Passage via Mill Creek (<1 km). There are two inlet streams: Porterfield Creek (ADF&G stream number 10740-10070-0010-2010) flows southwest 11 km to the east end of Virginia Lake, and Glacier Creek (ADF&G stream number 10740-10070-0010-2006) flows west 13 km to the south side of Virginia Lake (Orth 1967). Mean annual precipitation is an estimated 280 cm, the lake watershed area encompasses approximately 83 km^2, and the hydraulic residence time or flushing rate is estimated at 4.2 months (Edmundson et al. 1991).

Project Sponsorship

Funding to evaluate the limnological and nutrient enrichment assessment program in 2000 was provided by the United States Forest Service through the Alaska Department of Fish and Game. This is the final report fulfilling contract obligations for Sikes Act Contract 43-0116-0-0043.

METHODS

Limnological Assessment

Sampling to evaluate the lake fertilization program was conducted on the lake at station A, with a replicate zooplankton sample collected at Station B (Figure 2). Physical data, water quality, and biological samples were collected on 3 May, 9 June, 5 July, 4 August, 8 September, and 10 October. All samples were analyzed at the ADF&G, Division of Commercial Fisheries, limnology laboratory in Soldotna, Alaska.

Physical Parameters

Measurements of underwater light penetration (footcandles) were recorded at 0.5 m intervals, from the surface to a depth equivalent to one percent of the subsurface light reading, using an International Light[2] IL1350 submarine photometer. Vertical light extinction coefficients (K_d) were calculated as the slope of the light intensity (ln of percent subsurface light) versus depth. The euphotic zone depth (EZD), the depth to which 1% of the subsurface light (photosynthetically available radiation [400-700 nm]) penetrates the lake surface (Schindler 1971), was calculated from the equation: EZD = 4.6205/ K_d (Kirk 1994). Euphotic volume (EV) is the product of the EZD and lake surface area and represents the volume of water capable of photosynthesis. Temperature and dissolved oxygen concentrations were recorded at 1 m depth intervals, from the lake surface to 50 m, using a Yellow Springs Instruments (YSI) model 58 meter calibrated each sampling trip with a 60 ml Winkler field titration (Koenings et al. 1987).

Water Quality

A Van Dorn sampler was used to collect water quality samples from the epilimnion at the 1 m depth, and from the mid-hypolimnion. Eight liters of water were collected from each depth, stored in pre-cleaned polyethylene carboys, transported to Ketchikan, and then filtered or preserved for laboratory analysis.

[2] Mention of trade names does not constitute endorsement by ADF&G but are included for scientific completeness.

Separate subsamples from each carboy were: (1) refrigerated for general tests and metals; (2) frozen for nitrogen and phosphorus analysis; and (3) filtered through a 0.7 µm particle retention glass fiber filter and frozen for analysis of dissolved nutrients (Koenings et al. 1987). Samples were analyzed for general qualities, metals, nutrients, and primary production by methods detailed in the Alaska Department of Fish and Game limnology field and laboratory manual (Koenings et al. 1987), and summarized in Edmundson et al. (1991), Zadina and Weller (1999), and Zadina and Heinl (2000).

Surface water samples were taken once monthly from May-October at Porterfield Creek just upstream of a fertilizer dispersion location (see Lake Fertilization below) and also downstream near the stream confluence with Virginia Lake. These samples were frozen for total phosphorus analysis.

Secondary Production

Zooplankton samples were collected using a 0.5 m diameter, 153 µm mesh, 1:3 conical net. Vertical zooplankton tows were pulled from a depth of 50 m to the surface at a constant speed of 0.5 m · sec^{-1}. The net was rinsed prior to removing the organisms, and all specimens were preserved in neutralized 10% formalin (Koenings et al. 1987). Samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology field and laboratory manual (Koenings et al. 1987), and summarized in Edmundson et al. (1991), Zadina and Weller (1999), and Zadina and Heinl (2000).

Lake Fertilization

Nutrient additions to Virginia Lake were based on estimates of yearly phosphorus loading (P in mg · m^{-2} · yr^{-1}) calculated after Vollenweider (1976):

surface specific loading:

$$L_p = [\mathrm{P}]_c^{sp} Q_s \left(1 + \sqrt{\bar{z}/Q_s}\right)\text{; and}$$

surface critical loading:

$$L_c = \left(10 \text{ mg P/m}^3\right) Q_s \left(1 + \sqrt{\bar{z}/Q_s}\right);$$

where: $[\mathrm{P}]_C^{SP}$ = spring overturn total P (mg · m^{-3}),

Q_s = $\bar{z}/T_w$,

T_w = water residence time (0.35 yr),

$\bar{z}$ = mean depth (27.5 m), and

10 mg P/m^3 = lower critical phosphorus level.

The addition of nutrients in 2000 was based on 60% of the critical load, and is equal to:

$$0.6L_c ? L_p$$

The recommended quantity of fertilizer to be applied in 2000, based on a spring overturn total of 4.5 mg P · m^{-3}, was 3.0 tons (120 50-lb boxes) of 8-24-8 solid, controlled release fertilizer (CRF), and 14.1 tons (85 30-g drums) of 32-0-0 liquid fertilizer (Zadina and Heinl 2000).

Juvenile Sockeye Salmon Assessment

Rearing Fry Population

The distribution and abundance of rearing sockeye salmon fry was estimated by hydroacoustic and mid-water trawl sampling using the same methods described by Zadina and Weller (1999). Virginia Lake was divided into ten sampling areas based on surface area. Sample design consisted of a series of ten stratified, randomly chosen orthogonal transects across the lake, one from each sampling area. Transect sampling was conducted during post-sunset darkness in one night. A constant boat speed of about 2.0 m sec^{-1} was attempted for all transects. A Biosonics DT-4000™ scientific echosounder (420 kHz, 6? single beam transducer) with Biosonics Visual Acquisition © version 4.0.2 software was used to collect data. Ping rate was set at 5 pings sec^{-1} and pulse width at 0.4 ms. Data were analyzed using Biosonics Visual Analyzer © version 4.0.2 software after returning to the office. A 2 m ? 2 m elongated trawl net was used for pelagic fish sampling. Trawl depths and duration were determined by fish densities and distributions throughout the lake based on observations during the hydroacoustic survey.

Lake Rearing Model

This report uses the ZB-EZD model (see Zadina and Weller 1999) that utilizes zooplankton biomass and euphotic zone depth to estimate the potential sockeye salmon fry rearing capability of the lake.

$$SB = 1.95(ZB) + 15.5(EZD) - 183.0; \ r^2 = 0.94$$

where: SB = total smolt biomass (kg · km^{-2}),
ZB = weighted seasonal mean zooplankton biomass (mg · m^{-2}), and
EZD = seasonal mean euphotic zone depth (m).

The total potential smolt biomass is estimated by multiplying the calculated SB by the total lake area (km^2). Since sockeye salmon fry do not normally rear in water less than 5 m deep, it is logical to exclude the littoral zone from the total lake area when making this calculation. Virginia Lake has a surface area of 2.49 km^2 that covers depths greater than 5 m. Thus the total potential smolt biomass of Virginia Lake will be the SB multiplied by 2.49 km^2. Maximum smolt production assumes an individual fish size of 2.4 g. The potential maximum number of smolt that can be produced at Virginia Lake will be calculated by taking the estimated total smolt biomass and dividing by 2.4 g. Optimum smolt production assumes an individual fish size of 4.0 g. The potential optimum number of smolt that can be produced at Virginia Lake will be calculated by taking the estimated total smolt biomass and dividing by 4.0 g.

This model, based on current physical and biological information, allows a comparison of the potential to the actual sockeye salmon fry rearing population (estimated from hydroacoustic sampling). The survival rate from fall rearing fry to smolt is assumed to be 70% (Geiger and Koenings 1991). Therefore the potential fall fry population (the number of fry the lake can support) can be estimated by taking the maximum or optimum smolt production and dividing by 70%.

Projected Returns and Marine Survival

Projected adult returns at Virginia Lake were calculated from the hydroacoustic estimate of the rearing fall fry population, and based on standard fry-to-smolt and marine survival assumptions for sockeye salmon (Koenings et al. 1989; Geiger and Koenings 1991). The age at adult return assumptions derived from previous sockeye salmon work at Hugh Smith and McDonald Lakes (Zadina and Haddix 1989) are presented in Table 1. A matrix was constructed using multiple brood years to estimate adult returns by year.

RESULTS

Limnological Assessment

Physical Parameters

The euphotic zone depth (EZD) ranged from 6.19 m (8 September) to 13.70 m (5 July), with a seasonal mean depth of 9.54 m. Euphotic volume (EV) was estimated at $24.49 \cdot 10^6$ m^3 or 24.49 EV units. This volume, capable of photosynthesis, represents 34.6% of the total lake volume. The thermocline depth ranged from 20 to 30 m. The lake was isothermic in May, and approaching isothermic in October. Dissolved oxygen levels were normal (Figure 3).

General Water Quality and Nutrient Concentrations

General water quality parameters and metal concentrations continued to be within the range regarded as normal for stained oligotrophic coastal Alaska lakes (Tables 2 and 3; see Edmundson et al. 1991; Zadina et al. 1992). The slightly acidic pH (mean 6.4), low conductivity, and low alkalinity indicated soft water; and the color (mean 15 Pt units) and iron concentrations (mean 101 $\mu g \cdot L^{-1}$) were characteristic of an organically stained lake.

Phosphorus is the primary element controlling lake productivity because it is the least abundant element of the nutrients required for algal growth in Virginia Lake. The concentration of total phosphorus was fairly stable through the season (Table 2). The concentrations of filterable reactive phosphorus (FRP, the most available form of phosphorus for algal uptake, Koenings et al. 1987), and total filterable phosphorus (TFP), were low, but within normal ranges for Virginia Lake, and fairly stable through the season (Table 2).

Total nitrogen levels were highest in May and June (?200 $\mu g \cdot L^{-1}$) decreased to a low in August, then increased again through October (Table 2). Despite the drop in total nitrogen in August, the atomic ratio of nitrogen to phosphorus (55:1; Figure 4) was still within the desired range for promotion of growth by the appropriate phytoplankton. The mean seasonal total nitrogen concentration was the highest we have recorded at Virginia Lake since 1989 (Table 3). Ammonia, which contains both the ammonium ion and ammonia, is the preferred form of nitrogen for uptake by phytoplankton (Koenings et al. 1987). Ammonia levels were fairly low in September, though the overall mean seasonal concentration (12.5 $\mu g \cdot L^{-1}$) was the highest since studies began at Virginia Lake. The nitrate + nitrite concentration was the highest, and the total Kjeldahl nitrogen (TKN) concentration the second highest, that we have recorded at Virginia lake since 1989.

The concentrations of reactive silicon (required for the formation of frustrule cell structure by diatoms) were fairly stable through the entire season, and relatively high compared to other years (Tables 2 and 3). The concentration of organic carbon, which estimates the amount and energy content of organic material in the lake (Koenings et al. 1987), was similar to other years (Table 3).

Total phosphorus concentrations from samples at Porterfield Creek are shown in Table 4.

Primary and Secondary Production

The mean epilimnion concentration of chlorophyll a in 2000 was relatively low and ranged from 0.13 to 0.76 $\mu g \cdot L^{-1}$ (seasonal mean 0.46 $\mu g \cdot L^{-1}$; Table 5). The macrozooplankton community of Virginia Lake in 2000 comprised two species of Copepods (*Cyclops* sp. and *Diaptomus franciscanus*), the Cladoceran *Bosmina longirostris*, and unspecified Cladocerans of the subfamily Chydorinae (Table 6). Total zooplankton productivity at Virginia Lake was below the 14-year average (Figures 5 and 6). The proportions of the total zooplankton density and biomass that were Cladocerans were also below average (Figures 7 and 8). Cladocerans are the preferred prey of sockeye salmon fry (Koenings and Burkett 1987). The mean body size of *Bosmina* in July and August were slightly below the 4.0 mm minimum threshold size for elective feeding by sockeye salmon fry (Koenings and McDaniel 1983). This suggests that Bosmina zooplankters were being heavily preyed upon at that time (Edmundson et al. 1991).

Lake Fertilization

During the 2000 field season a total of 14.3 tons (86 30-g drums) of 32-0-0 liquid fertilizer was applied to the lake at an average rate of 162 gallons per week from 19 May-2 September (Appendix Table A.1), using the same methods described by Zadina and Weller (1999).

The application of 120 50-lb boxes of 8-24-8 CRF was done in a similar manner as in 1999 (Zadina and Heinl 2000). The CRF was divided into five equal portions, then applied once a month from early May-early September: 75% was placed in the littoral area of the upper half of the lake (25% was placed in a box near shore, 25% was suspended from bags on logs, and 25% was simply spread loosely in shallow water along the lake shore); and 25% was placed approximately 6.4 km upstream in Porterfield Creek (Appendix Table A.1).

Juvenile Sockeye Salmon Assessment

A total lake population of 169,000 sockeye salmon fry was estimated from the hydroacoustic survey conducted on 26 September 2000 (Table 7). No sockeye salmon fry were captured during one 30-minute mid-water trawl at 10 m, and only two were caught in a second, 35 minute trawl at the same depth. The small sample size was due primarily to the low densities of sockeye salmon fry (1 fry $\cdot$ 418 m^{-3}) in the lake. Since no other species of fish were sampled in our trawls, we assumed that all targets that fell within a target strength range of –50 dB to –68 dB during hydroacoustics were sockeye salmon fry. This population of fry is expected to produce approximately 118,000 smolt in spring 2001, based on 70% over-winter survival.

Using the ZB-EZD model, we estimate that Virginia Lake could potentially support a maximum 219,000 fall fry, which translates to 154,000 smolt at an average weight of 2.4 g. We also estimate that the optimal rearing capacity in 2000 was 132,000 fall fry, which translates into 92,000 smolt at an optimum weight of 4.0 g.

Adult Sockeye Salmon Assessment

The total adult return forecast for 2001 is estimated at 14,175 (36% enhanced from the last fry plants in 1996) sockeye salmon based on 12% marine survival (Table 8).

DISCUSSION

The primary intention of nutrient additions to Virginia Lake in 1998, 1999, and 2000, was not to increase the sockeye salmon fry forage base (although sockeye salmon fry would certainly benefit from this), but to increase all trophic levels in Virginia Lake to ultimately benefit the resident cutthroat trout population. Nutrient additions to Porterfield Creek and in the littoral area of Virginia Lake most likely boosted trophic levels in those areas to some (unmeasured) degree, but how the cutthroat trout populations have been affected by nutrient enhancement is not known.

Samples from the limnetic portion of Virginia Lake throughout the 2000 season showed that concentrations of total phosphorus (Table 2) and chlorophyll a (Table 5), and both zooplankton density (Figure 5) and biomass (Figure 6) were relatively low. In fact it appears that conditions were most similar to years when the lake was not fertilized at all (1989, 1990, and 1997). Similar results were also obtained in 1999 when the lake was fertilized at 50% of the critical phosphorus load with a mixture of liquid and solid fertilizer (Zadina and Heinl 2000). Thus we assume that the lower fertilizer loading rate, including the use of solid fertilizer (comprising all of the added phosphorus) placed solely in the littoral zone of the lake, has not clearly elevated the lake's limnetic phytoplankton and zooplankton productivity.

While zooplankton production was below average (for fertilized years) in 2000, there appeared to be sufficient food for the number of sockeye salmon fry present. The estimated sockeye salmon fry population of 169,000, based on fall hydroacoustics, fell within the range of maximum (219,000) and optimum (132,000) numbers of fry that we estimate the lake could support based on analysis of light penetration and zooplankton biomass (ZB-EZD model).

The original sockeye salmon production potential of Virginia Lake was estimated at 26,000-37,000 adult sockeye (Edmundson et al. 1991). This estimate was based solely on the two original models. The EV model (Koenings and Burkett 1987), that only used physical characteristics of sockeye nursery lakes and did not take into account the biological productivity of the study lake, and the ZB model (Koenings and Kyle 1997) that utilized the standing crop of zooplankton in sockeye nursery lakes. The ZB model was driven by a few very productive lakes in Southcentral Alaska and Idaho (Stan Carlson, Biometrician, ADF&G, Soldotna, pers. comm., 1997). Thus, the two models predict an unrealistic productivity index for most coastal oligotrophic lakes in Southeast Alaska. However, these were the only models available when studies to estimate production at Virginia Lake were initiated. Analysis using the ZB-EZD model with zooplankton productivity data for the original pre-stocking (1987-1988), post-fertilizer (1997) and low loading rate fertilizer (1998-2000) years suggests the estimated adult sockeye salmon production potential of Virginia Lake may only reach a maximum annual return of 10,000 – 17,000 fish. Virginia Lake is a naturally nutrient poor system, with a rapid flushing rate (Edmundson et al. 1991). It is our opinion that the lake will never be as productive in its natural state as the original models predicted. There is a possibility that future runs could be higher than this level if either: a) the system receives increased salmon escapement leading to the increased marine derived nutrients required for good lake productivity; or b) with proper nutrient additions and further enhancement with sockeye fry or pre-smolt.

RECOMMENDATIONS

Suggested fertilizer quantities for 2001 are dependent on desired loading rates (Table 9). These suggested amounts are based on Vollenweider's (1976) loading equations and assume a 2001 spring overturn period total phosphorus level of 3.90 mg $\cdot$ m^{-3}. This phosphorus level is estimated from water samples taken on 10 October 2000 (Table 2). We use the fall water sample because the collection of water samples and analysis of phosphorus concentrations in the spring cannot be accomplished in time to purchase and transport the fertilizer prior to the growing season. Should the goal of future nutrient additions to Virginia Lake include boosting limnetic zooplankton populations for the benefit of sockeye salmon fry, then we recommend that the fertilizing regime switch back to the use of liquid fertilizer. Specifically, liquid 20-5-0 fertilizer should be used so that phosphorus is placed into the limnetic area of the lake where phytoplankton and zooplankton populations can utilize the nutrients directly. If the decision to use CRF solid fertilizer is made then distribution should follow the recommendations from the 2000 season (Zadina and Heinl 2000).

Limnological evaluation should continue if nutrient additions proceed at Virginia Lake. Evaluation of sockeye salmon juveniles, returning adult salmon, and resident salmonids should also continue.

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TABLES

Table 1. Age distribution assumptions of adult sockeye salmon returning to Virginia Lake by brood year and return year.

Brood Year	Smolt Years	Projected Adult Age Distribution	Adult Age Class	Return Year
1995	1997	10.5%	1.2	1999
	or	65.1%	1.3	2000
	1998	5.5%	2.2	2000
		18.0%	2.3	2001
1996	1998	10.5%	1.2	2000
	or	65.1%	1.3	2001
	1999	5.5%	2.2	2001
		18.0%	2.3	2002

Table 2. Summary of general water quality parameters, metal concentrations, and nutrient concentrations within the epilimnion (1 m) and mid-hypolimnion at Virginia Lake, Station A, 2000.

Date	3-May		9-Jun		5-Jul		4-Aug		8-Sep		10-Oct	
Depth	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo	1 m	Hypo
pH (units)	6.6	6.6	6.5	6.3	6.6	6.3	6.2	6.1	6.4	6.2	6.9	6.5
Conductivity (µmhos · cm^{-1})	26	27	26	29	23	27	21	29	24	30	22	29
Alkalinity (mg · L^{-1})	10.2	10.8	9.7	10.2	8.5	9.8	7.4	10.5	9.6	11.1	9.6	11.0
Turbidity (NTU)	0.6	0.7	0.4	0.5	0.9	1.7	0.9	0.8	0.8	0.7	1.2	1.5
Color (Pt units)	17	17	11	18	10	17	12	15	19	14	18	14
Calcium (mg · L^{-1})	4.3	4.0	4.3	4.1	3.6	3.9	3.2	4.3	3.8	4.7	3.6	4.4
Magnesium (mg · L^{-1})	0.3	0.5	0.4	0.3	0.5	0.6	0.5	0.6	0.4	0.5	0.3	0.4
Total Iron (µg · L^{-1})	135	156	53	127	49	132	65	136	66	116	73	109
Total P (µg · L^{-1})	3.4	3.2	2.2	3.0	3.2	3.0	4.7	4.5	4.0	3.3	4.2	3.6
TFP (µg · L^{-1})	2.7	2.3	1.6	4.8	2.4	3.9	2.3	2.4	2.7	2.7	2.5	2.6
FRP (µg · L^{-1})	1.8	1.3	0.9	3.5	1.1	2.3	1.2	1.6	1.3	1.7	1.7	1.3
TKN (µg · L^{-1})	104.7	96.3	132.9	92.2	107.8	107.8	76.7	113.1	85.8	112.1	126.7	116.2
Ammonia (µg · L^{-1})	9.0	11.4	12.6	14.1	12.5	15.6	13.8	14.1	5.7	6.1	13.5	21.8
Nitrate+Nitrite (µg · L^{-1})	127.9	113.1	115.3	126.4	70.7	125.8	40.3	124.0	51.0	134.1	55.0	130.8
Total N (µg · L^{-1})	232.6	209.4	248.2	218.6	178.5	233.6	117.0	237.1	136.8	246.2	181.7	247.0
Reactive Silicon (µg · L^{-1})	1,421	1,406	1,091	1,340	914	1,273	889	1,256	971	1,265	1,100	1,334
Carbon (µg · L^{-1})	130	176	82	79	96	64	124	79	133	102	99	53

Table 3. Comparison of the seasonal mean general water quality parameters, metal concentrations, and nutrient concentrations, at Virginia Lake, Station A, 1989-1990, and 1992-2000.

	1989[a]	1990[a]	1992[b]	1993[b]	1994[b]	1995[b]	1996[b]	1997[a]	1998[c]	1999[d]	2000[e]
pH (units)	6.5	6.6	6.4	6.5	6.3	6.4	6.3	6.8	6.8	6.5	6.4
Conductivity (μmhos · cm^{-1})	26	25	23	24	26	29	29	27	26	26	26
Alkalinity (mg · L^{-1})	7.5	9.0	6.8	9.0	8.6	10.9	10.0	11.7	11.1	10.8	9.9
Turbidity (NTU)	0.8	2.0	1.0	2.2	1.1	1.3	0.9	0.7	0.7	0.9	0.9
Color (Pt units)	15	NA	13	12	16	13	16	15	14	14	15
Calcium (mg · L^{-1})	4.3	4.1	3.9	4.0	4.1	4.4	4.1	4.0	3.9	4.1	4.0
Magnesium (mg · L^{-1})	?0.2	0.5	0.7	0.5	0.6	0.7	0.4	0.4	0.3	0.4	0.4
Total Iron (μg · L^{-1})	130	175	121	257	152	161	146	87	67	123	101
Total P (μg · L^{-1})	4.4	5.4	5.0	9.5	5.5	4.6	5.4	2.6	4.2	5.3	3.5
TFP (μg · L^{-1})	3.0	2.8	2.5	3.2	4.3	2.9	3.5	2.6	3.0	3.2	2.7
FRP (μg · L^{-1})	2.3	2.6	1.1	1.8	2.2	1.4	2.3	2.5	2.1	3.0	1.6
TKN (μg · L^{-1})	53.5	53.8	68.4	134.3	79.2	67.6	97.9	65.8	69.9	78.3	106.0
Ammonia (μg · L^{-1})	8.0	4.2	9.1	11.9	6.8	3.3	9.9	7.7	4.2	10.2	12.5
Nitrate+Nitrite (μg · L^{-1})	75.0	76.7	64.4	65.6	65.7	98.7	71.0	68.7	59.3	73.0	101.2
Total N (μg · L^{-1})	128.5	128.8	132.8	199.9	139.8	150.5	168.9	134.5	129.2	151.4	207.2
Reactive Silicon (μg · L^{-1})	1,124	843	883	1,029	976	1,073	834	1,159	1,082	1,209	1,188
Carbon (μg · L^{-1})	NA	NA	NA	NA	NA	NA	NA	NA	111	129	101

[a] In 1989, 1990, and 1997 Virginia Lake was not fertilized.
[b] From 1992-1996 Virginia Lake was fertilized at 90% of the critical phosphorus load with liquid fertilizer.
[c] In 1998 Virginia Lake was fertilized at 50% of the critical phosphorus load with liquid fertilizer.
[d] In 1999 Virginia Lake was fertilized at 50% of the critical load with a combination of liquid and solid fertilizer.
[e] In 2000 Virginia Lake was fertilized at 60% of the critical load with a combination of liquid and solid fertilizer.

Table 4. Comparison of the total phosphorus concentrations in surface samples taken at the upstream and downstream stations in Porterfield Creek, Virginia Lake, 2000.

Sample Date	Total P (μg · L^{-1}) Upper Station	Lower Station
12-May	13.9	2.8
12-Jun	33.2	6.5
10-Jul	3.0	5.8
4-Aug	2.8	2.5
5-Sep	9.3	4.2
18-Oct	2.8	5.4

Table 5. Summary of algal pigment concentrations (µg · L $^{-1}$) at Virginia Lake, Station A, 1992-2000.

		1992		1993		1994		1995		1996		1997		1998		1999		2000	
Month	Depth	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a	Chl a	Phaeo a
May	1			0.17	0.12			0.31	0.12	0.28	0.17	0.45	0.26			0.16	0.02	0.32	0.21
	2							0.32	0.12	0.24	0.17	0.45	0.29			0.54	0.09	0.33	0.22
	MEU			0.19	0.09			0.34	0.12	0.27	0.17	0.45	0.26			0.36	0.15	0.27	0.14
	EZD			0.09	0.05			0.31	0.11	0.03	0.09	0.35	0.26			0.19	0.05	0.11	0.09
	Hypo			0.02	0.03			0.03	0.04	0.25	0.18	0.33	0.24			0.00	0.02	0.02	0.05
June	1	0.84	0.47	1.20	0.38	3.57	0.03	1.80	0.47	6.36	1.26	0.16	0.09	0.19	0.20	0.54	0.24	0.38	0.12
	2					2.58	0.15							0.38	0.33				
	MEU	1.01	0.46	0.76	0.43	2.56	0.54	0.96	0.46	6.91	1.44	0.41	0.20	0.88	0.71	0.57	0.15	0.56	0.11
	EZD	0.66	0.35	0.48	0.37	2.76	0.56	0.93	0.36	7.09	1.16	0.48	0.27	2.06	1.50	0.48	0.12	0.27	0.15
	Hypo	<0.01	0.08			0.03	0.06	0.03	0.05	0.09	0.07	0.23	0.15	0.04	0.08	0.02	0.04	0.02	0.06
July	1	1.06	0.52	6.24	1.73	0.47	0.64	1.63	0.35	2.80	0.95	0.26	0.17	1.81	0.60	0.19	0.12	0.59	0.17
	2							1.56	0.39			0.23	0.17	2.23	0.32	0.34	0.20		
	MEU	1.24	0.85	0.99	0.61	0.47	0.50	1.97	0.88	1.99	0.83	0.29	0.25	3.14	0.05	0.23	0.09	0.79	0.13
	EZD	0.72	1.21	3.59	0.62	1.04	1.04	3.93	3.30	1.55	1.05	0.52	0.46	0.63	0.46	0.43	0.09	1.53	0.36
	Hypo	0.08	0.14	0.09	0.12	0.13	0.15	0.23	0.24	0.39	0.23	0.15	0.08	0.10	0.17	0.05	0.08	0.03	0.07
Aug.	1	1.13	0.99	1.14	0.87	2.15	0.73	1.83	0.44	3.59	0.70	0.38	0.27	0.29	0.19	0.12	0.11	0.76	0.16
	2					1.86	0.59	2.09	0.57	3.35	0.60			0.55	0.40	0.10	0.03	0.69	0.12
	MEU	1.25	1.11	0.76	0.69	1.82	0.51	1.90	0.70	2.87	0.63	0.52	0.39	0.25	0.23	0.35	0.09	0.63	0.14
	EZD	1.71	1.34	1.48	0.77	1.47	0.49	1.37	0.71	2.26	1.29	0.62	0.47	0.24	0.16	0.29	0.28	0.48	0.16
	Hypo	0.05	0.23	0.22	0.27	0.55	0.39	0.10	0.22	0.35	0.31	0.12	0.14	0.03	0.09	0.04	0.05	0.14	0.32
Sept.	1	0.50	0.19	0.37	0.21	0.82	0.34	6.30	1.33	9.82	0.01	0.34	0.29	0.55	0.32	0.49	0.10	0.13	0.09
	2					0.88	0.36			12.71	0.21	0.31	0.28	0.69	0.38	0.51	0.12		
	MEU	0.63	0.31	0.34	0.19	1.06	0.20	7.20	0.42			0.43	0.31	0.43	0.31	0.68	0.16	0.51	0.10
	EZD	0.48	0.29	0.48	0.36	1.76	0.74	9.21	3.06	11.23	0.50	0.21	0.26	0.28	0.11	0.24	0.11	0.39	0.26
	Hypo	0.05	0.19	<0.01	0.40	0.16	0.19	0.42	0.46	0.17	0.12	0.05	0.07	0.04	0.09	0.02	0.03	0.01	0.03
Oct.	1	0.19	0.15	0.23	0.35	0.24	0.13	2.36	0.87	5.00	0.28					0.23	0.06	0.56	0.13
	2							2.15	0.77							0.19	0.12		
	MEU	0.22	0.14			0.23	0.13	1.80	0.76	5.05	0.36					0.14	0.09	0.31	0.13
	EZD	0.19	0.13	0.18	0.31	0.16	0.14	1.69	0.62	0.24	0.10					0.18	0.10	0.16	0.11
	Hypo	0.03	0.12	0.08	0.24	0.04	0.07	0.17	0.15	5.22	0.01					0.02	0.04	0.03	0.06

Table 6. Seasonal mean macrozooplankton density and weighted mean biomass distribution at Virginia Lake, 2000.

Species		Date						Mean Density		Weighted Mean Biomass	
		3-May	9-Jun	5-Jul	4-Aug	8-Sep	10-Oct	$n \cdot m^{-2}$	Percent	$mg \cdot m^{-2}$	Percent
Copepoda											
Diaptomus	Density (No. $\cdot$ m^{-2})	19,656	10,978	3,600	1,333	637	77	6,047	18.1%	44.3	47.2%
	Size (mm)	0.97	1.30	1.60	1.79	1.85	1.85				
Diaptomus – ovig.	Density (No. $\cdot$ m^{-2})			170	459	679	179	248	0.7%	6.8	7.3%
	Size (mm)			1.08	1.93	1.90	1.84				
Cyclops	Density (No. $\cdot$ m^{-2})	6,283	15,784	6,572	1,562	6,113	8,227	7,423	22.2%	14.7	15.7%
	Size (mm)	0.90	0.64	0.62	0.78	0.90	0.87				
Cyclops – ovig.	Density (No. $\cdot$ m^{-2})	85	247	77		255	280	157	0.5%	0.7	0.8%
	Size (mm)	1.05	1.10	0.55		1.15	1.16				
Cladocera											
Bosmina	Density (No. $\cdot$ m^{-2})	2,930	3,346	14,977	77,688	11,505	3,821	19,044	57.0%	26.5	28.2%
	Size (mm)	0.49	0.41	0.39	0.38	0.46	0.44				
Bosmina – ovig.	Density (No. $\cdot$ m^{-2})		0	170	1,291		0	243	0.7%	0.5	0.5%
	Size (mm)		0.30	0.27	0.48		0.30				
Chydorinae	Density (No. $\cdot$ m^{-2})	43			688	128	637	249	0.7%	0.3	0.3%
	Size (mm)	0.36			0.37	0.35	0.35				
Chydorinae – ovig.	Density (No. $\cdot$ m^{-2})				34			6	0.0%	0.0	0.0%
	Size (mm)				0.20						

Table 7. Fall sockeye salmon fry population estimates at Virginia Lake, 1989-2000.

Year	Total Limnetic Fish Population	Fry Population[a]	m^3 per Fry
1989[b]	282,147	270,128	262
1990[b]	138,800	138,800	509
1991[b]	121,000	121,000	584
1992[b]	150,250	127,562	554
1993[b]	no fall survey		
1994[b]	no fall survey		
1995[b]	312,966	312,966	226
1996[b]	no fall survey		
1997	109,539	109,539	645
1998	102,220	102,220	692
1999	115,592	115,592	612
2000	168,571	168,571	419

[a] Population of fish based on trawl samples - some stickleback captured in 1989 and 1992.
[b] Fry stocked in lake.

Table 8. The 2001 forecasted adult return of Virginia Lake sockeye salmon by age class and hatchery and wild components based on the projected smolt population.

Return Year	Brood Year	Age Class	Stocked	%	Wild	%	Total Adult Return
2001	1995	2.3	5,096		1,656		6,752
2001	1996	1.3	0		5,843		5,843
2001	1996	2.2	0		541		541
2001	1997	1.2	0		1,039		1,039
Total			5,096	36%	9,079	64%	14,175

Table 9. Suggested fertilizer application amounts, based on various phosphorus loading rates, for the 2001 field season at Virginia Lake.

Percent of Critical Load	Tons of 8-24-8 needed	50lb bags of 8-24-8 needed	Amount for stream distribution	30-gal drums of 32-0-0 needed	Drums of 32-0-0 per week	**OR** 30-gal barrels of 20-5-0 needed to meet same rate
50%	2.2	88	22 bags	62	5	112
60%	4.2	168	42 bags	118	10	214
70%	6.2	248	62 bags	175	15	316
90%	10.2	407	102 bags	287	24	520

FIGURES

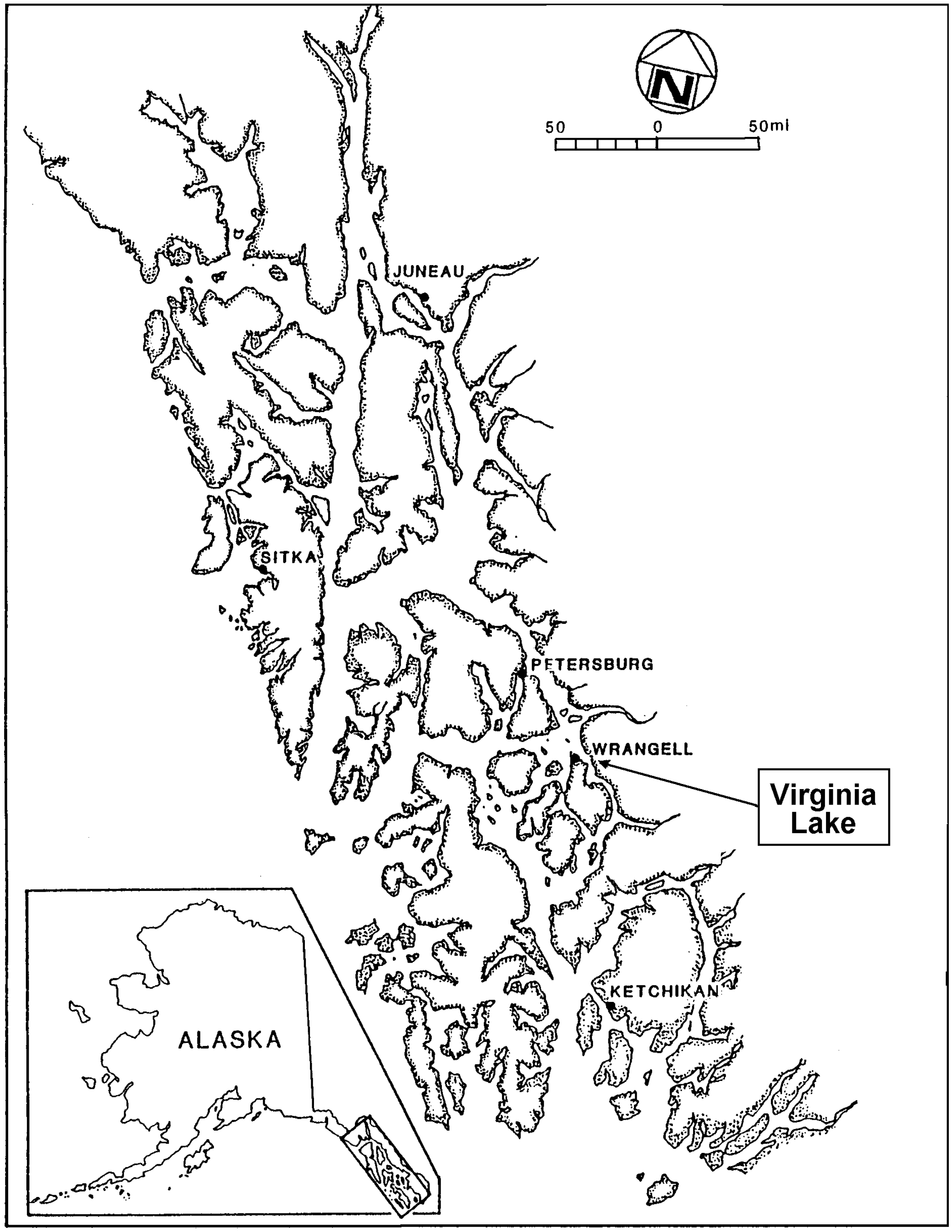

Figure 1. The geographic location of Virginia Lake, within the State of Alaska, and relative to cities within Southeast Alaska.

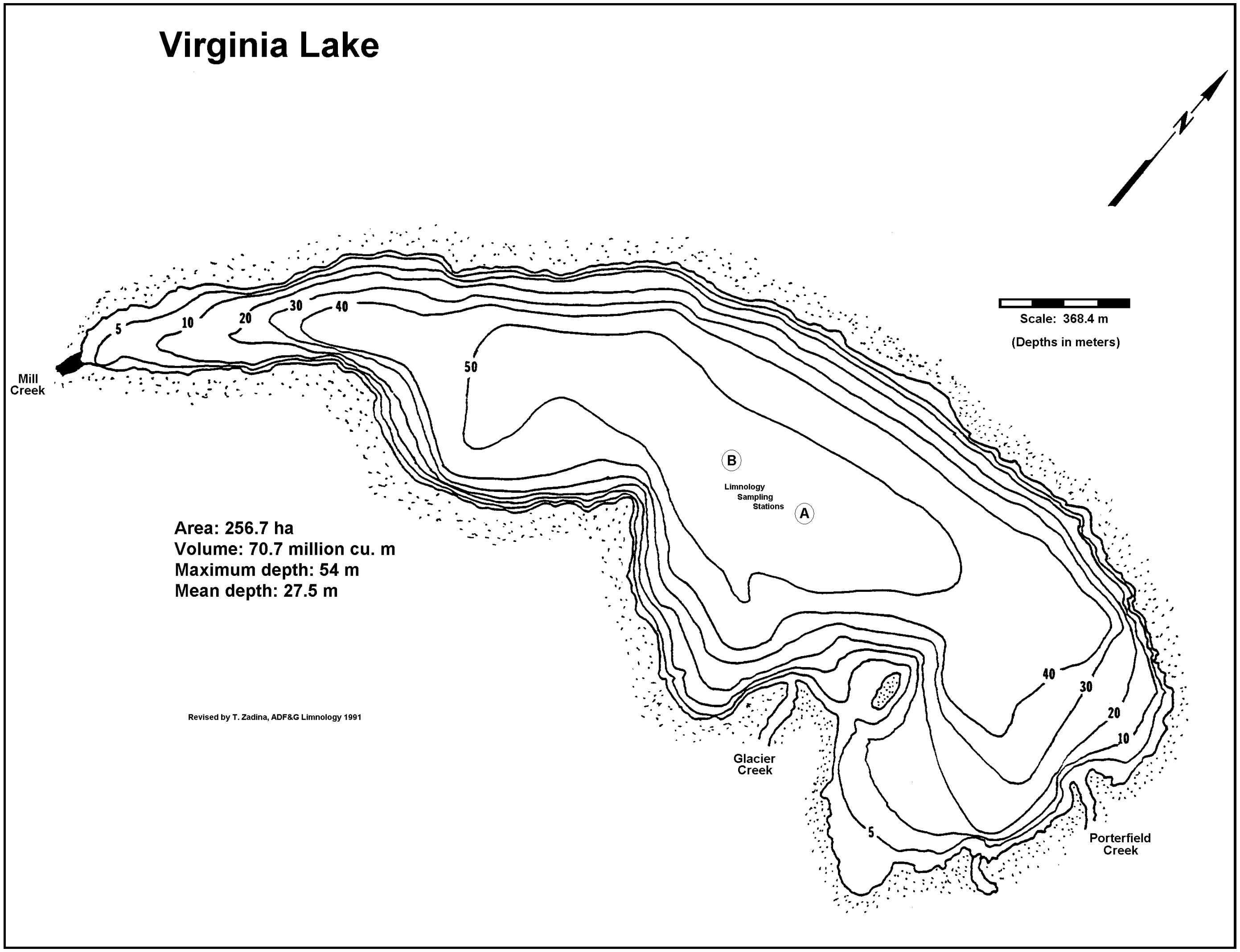

Figure 2. Bathymetric map of Virginia Lake, Southeast Alaska with limnology sampling stations.

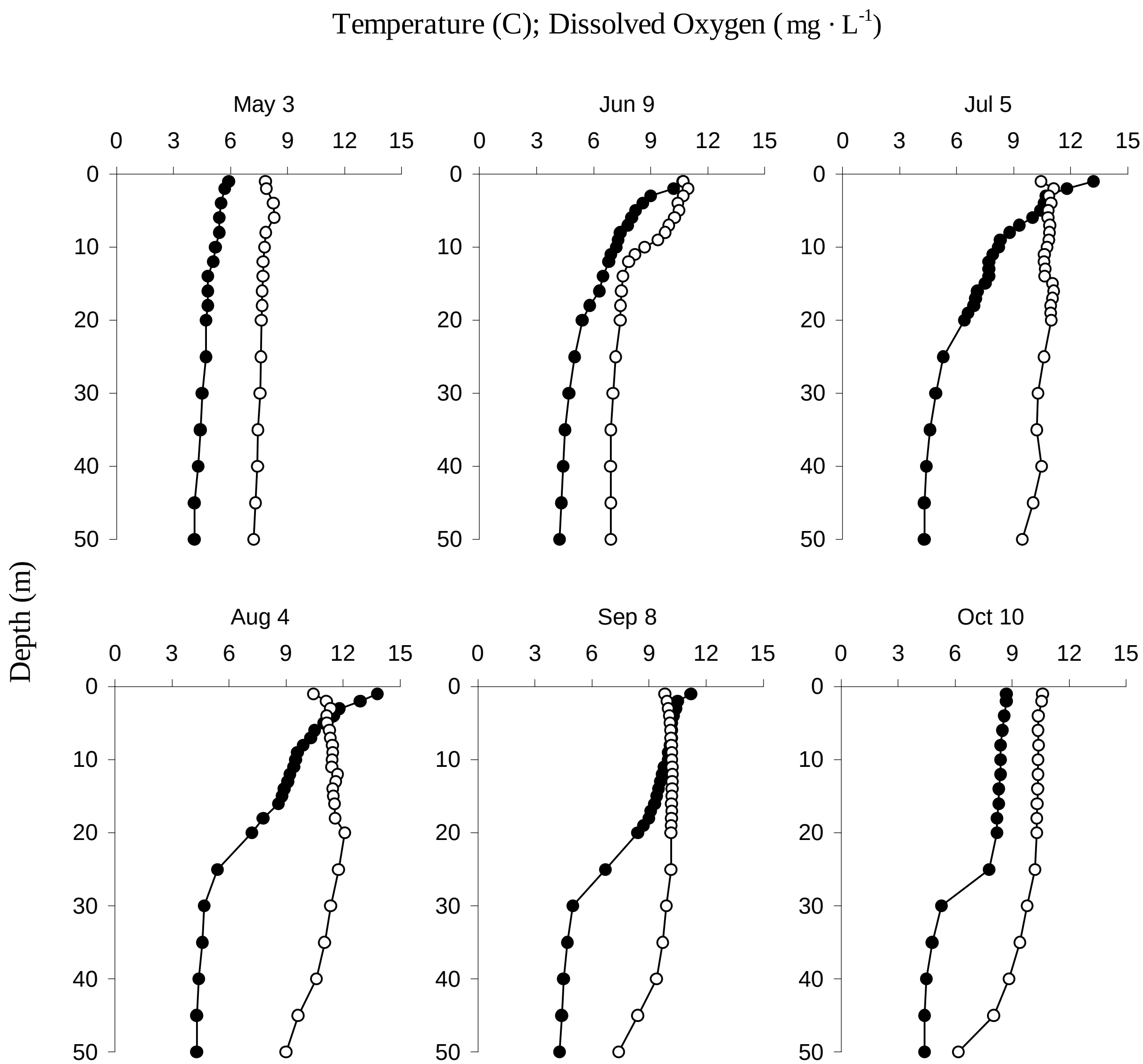

Figure 3. Seasonal temperature (C; closed circles) and dissolved oxygen (mg · L^{-1}; open circles) profiles in Virginia Lake, 2000.

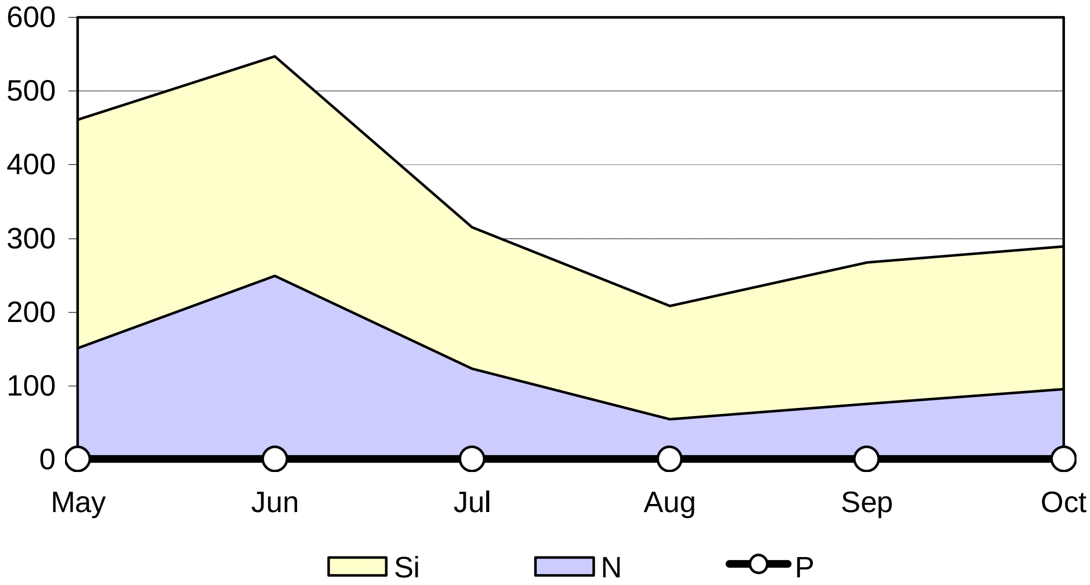

Figure 4. Monthly atomic concentration ratios of nitrogen (N), phosphorus (P; where P=1), and reactive silicon (Si) in the epilimnion at Virginia Lake, 2000.

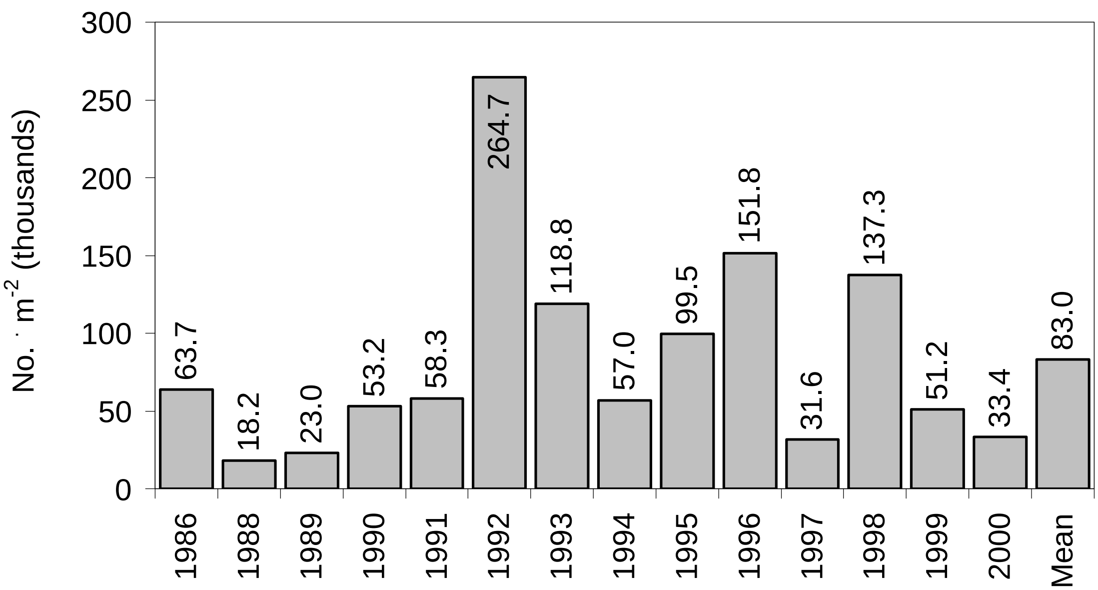

Figure 5. Mean seasonal macrozooplankton density at Virginia Lake, from 1986 to 2000, and for the 14-year mean.

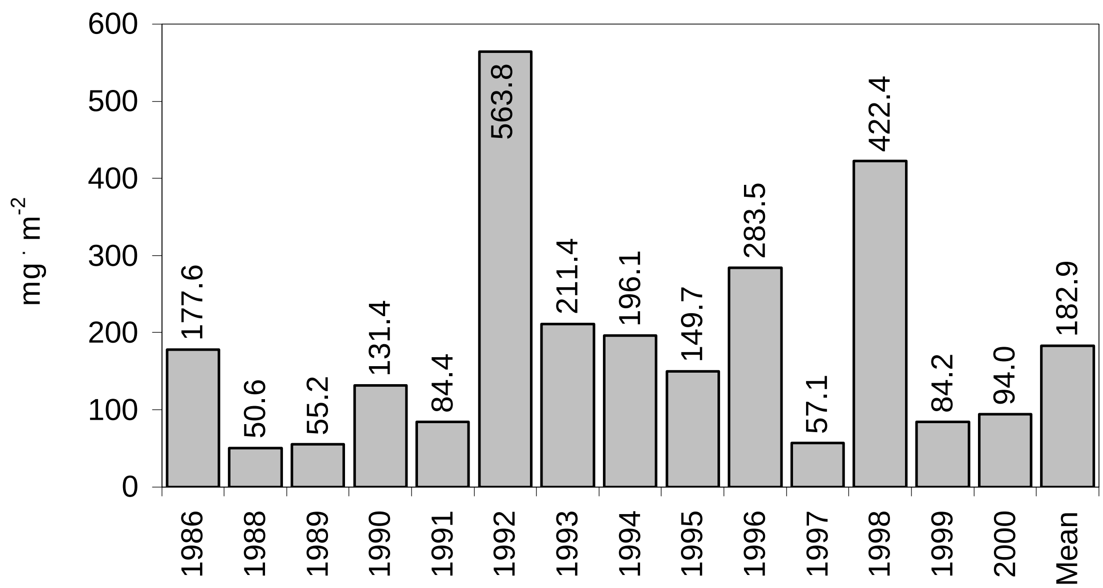

Figure 6. Mean seasonal macrozooplankton biomass at Virginia Lake from 1986 to 2000, and for the 14-year mean.

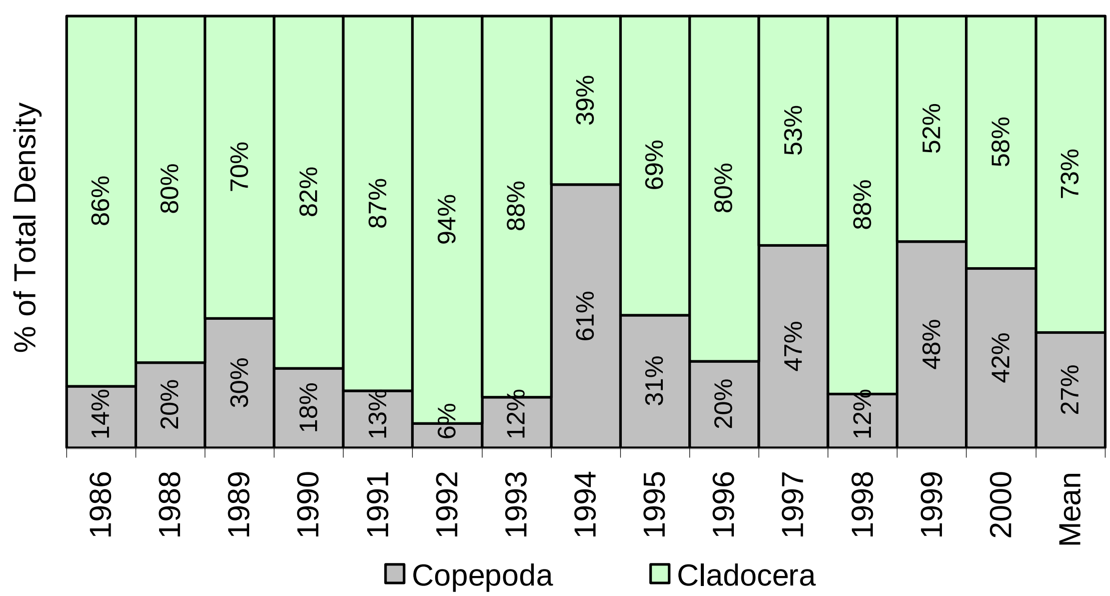

Figure 7. Mean seasonal macrozooplankton density distribution by plankter order at Virginia Lake, from 1986 to 2000, and for the 14-year mean.

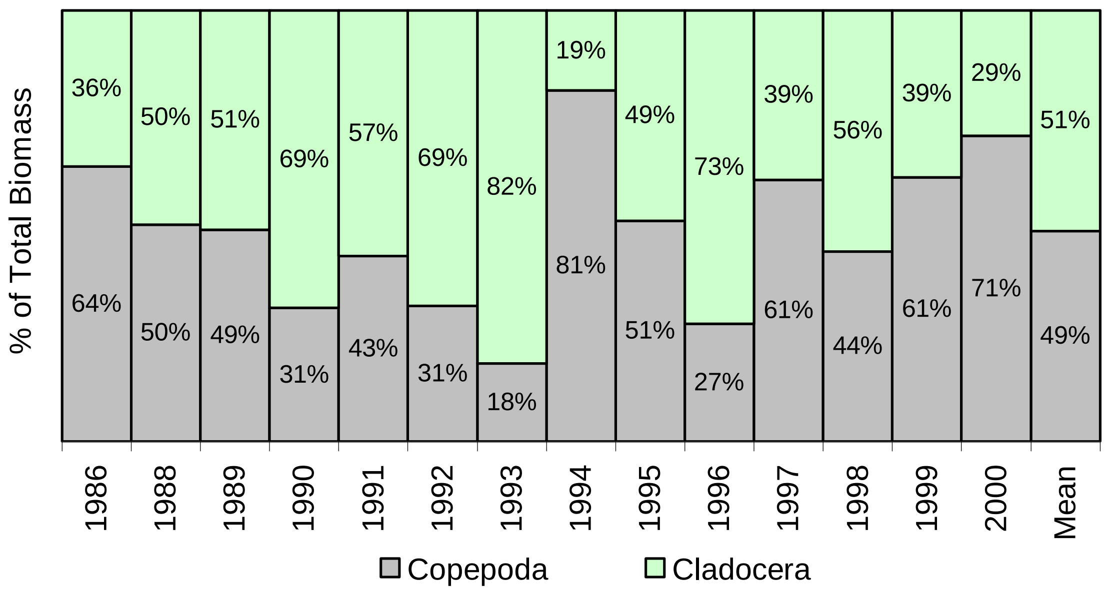

Figure 8. Mean seasonal macrozooplankton biomass distribution by plankter order at Virginia Lake, from 1986 to 2000, and for the 14-year mean.

APPENDIX

Appendix Table A. 1 Weekly fertilizer applications at Virginia Lake, 2000.

		Application of 50-lb Boxes 8-24-8 Solid Controlled Release Fertilizer[a]:			
Statistical Week	Gallons Liquid 32-0-0 Applied to Lake	Floating Box	Logs	Loose	Porterfield Creek
20		6	6	6	
21	180				6
22	150				
23	180				
24	150				
25	180	6	6	6	6
26	150				
27	180				
28	150	6	6	6	
29	180				6
30	150				
31	180				
32	150				6
33	180	6	6	6	
34	150				
35	180				
36	100				
37		6	6	6	6
Total	2,590	30	30	30	30

[a] All solid controlled release fertilizer was placed in the littoral zone of the lake (in a floating box, in bags attached to logs, and simply spread loosely in shallow water along the lake shore) and upstream of the lake in Porterfield Creek.

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